The 18th International Workshop on the H-Mode Physics

Andlinger Center, Princeton University, Princeton, NJ

A Possible Mechanism for the Edge Transport Barrier Formation: The story of Finite Larmor Radius Effects

W. W. Lee
Princeton Plasma Physics Laboratory, Princeton, NJ 08543

Sept. 20, 2022

The present work is partially supported by PPPL Theory Department

Abstract

In this presentation, our focus is on the use of our theory to compare with the experimental results on the formation of the H-mode pedestal as well as the reduction of the transport and, also, to compare with the poloidal flow measurements before the transition.

Here, instead of treating the H-mode physics as an initial value problem, we view it as a boundary value problem. The basic equations are the force balance equation and the gyrokinetic Poisson's equation.

Abstract (continued)

• It is commonly believed that sheared E x B flow is the reason for the improved confinement at the H-mode pedestal, e.g., the review article by Burrell [1].

• Lee and White [2] claim that the formation of the H-mode pedestal is the reason for the improved confinement which gives rise to the E x B flow. That's because the pedestal formation causes the charge separation between the electrons and the ions due to the Finite Larmor Radius (FLR) effects and results in a radial electric field well, Er, and thus the flow. The delicate force balance between the ion pressure gradient and gyroviscosity, makes the H-mode a force-free configuration.

• Here, we will justify our theory based on the FLR effects by comparing it with some recent experiments and those of Diallo *et al.* [3] on the sudden transition to the H-mode and Zweben *et al.* [4] on the lack of precursors before the transition.

• Simulation algorithms including the FLR physics are proposed for the gyrokinetic codes and gyrokinetic-MHD codes to verify our theoretical predictions as an initial value problem.

[1] K. H. Burrell, Phys. Plasmas **27**, 060501 (2020) and the references therein

[2] W. W. Lee and R. B. White, Phys. Plasmas **26**, 040701 (2019)

[3] A. Diallo *ét al*., Nucl. Fusion **57,** 066050 (2017)

[4] S. J. Zweben *ét al*., Phys. Plasmas **28**, 032304 (2021)

Outline of the Talk

1. The experimental observations of the H-mode and the prevailing understanding of the H-mode pedestal

2. Our FLR theory on the pedestal physics and experimental comparisons

3. Governing gyrokinetic Vlasov-Maxwell equations including FLR effects

4. Discussion on the numerical verifications of our theory

Eur. Phys. J. H 43, 523–549 (2018)
https://doi.org/10.1140/epjh/e2016-70064-9

THE EUROPEAN PHYSICAL JOURNAL H

The history of research into improved confinement regimes

F. Wagner[a]

Max Planck Institute for Plasma Physics, 85748 Garching bei München, Germany

The H-mode on ASDEX:

But suddenly at constant power and without interference from the outside the plasma jumped into a new regime where both particle and energy confinement improved. The time for transition was much shorter than the energy confinement time and could be as short as ~100 μs. This discrepancy in time scales pointed right away toward a bifurcating process.

Plasma Phys. Control. Fusion **40** (1998) 1429–1488. Printed in the UK PII: S0741-3335(98)57302-2

REVIEW ARTICLE

Experimental studies of the physical mechanism determining the radial electric field and its radial structure in a toroidal plasma

Katsumi Ida
National Institute for Fusion Science, Oroshi-cho Toki Gifu 509-52, Japan

In H-mode plasmas, the thermal transport is reduced and large temperature gradients are produced associated with a strong negative electric field shear localized at the plasma periphery.

The force balance equation in the steady state was used:

$$n_i e \mathbf{E} = \nabla p_i - n_i e \frac{\mathbf{V}_i \times \mathbf{B}}{c}$$

PHYSICS OF PLASMAS **16**, 056103 (2009)

Edge radial electric field structure and its connections to *H*-mode confinement in Alcator C-Mod plasmas[a)]

R. M. McDermott,[b)] B. Lipschultz, J. W. Hughes, P. J. Catto, A. E. Hubbard, I. H. Hutchinson, R. S. Granetz, M. Greenwald, B. LaBombard, K. Marr, M. L. Reinke, J. E. Rice, D. Whyte, and Alcator C-Mod Team
Plasma Science and Fusion Center, Massachusetts Institute of Technology, 175 Albany Street, Cambridge, Massachusetts 02139, USA

The results indicate that in H-mode the main ion pressure gradient is the dominant contributor to the E_r well and that the main ions have significant edge flow. C-Mod H-mode data show a clear correlation between deeper E_r wells, higher confinement plasmas, and higher electron temperature pedestal heights.

….. This is in keeping with the theory that E x B shear suppression is instrumental to the L-H transition.

Role of sheared $E \times B$ flow in self-organized, improved confinement states in magnetized plasmas

Cite as: Phys. Plasmas **27**, 060501 (2020); doi: 10.1063/1.5142734
Submitted: 16 December 2019 · Accepted: 8 April 2020 ·
Published Online: 23 June 2020

View Online Export Citation CrossMark

K. H. Burrell[a),b)]

AFFILIATIONS

General Atomics, P. O. Box 85608, San Diego, California 92186, USA

…..Theory for this portion of the plasma is particularly challenging because the gradient scale lengths, the turbulence mode widths, and the ion gyroradii are all comparable, which means that a plethora of effects must be considered simultaneously.

….. it is not often that a system self-organizes to reduce transport when an additional source of free energy is applied to it.

….. These experiments have clearly demonstrated that increased E x B shear causes reductions in turbulence and transport.

….. One specific issue concerning E x B shear in the plasma edge that needs further work is the effect of a nonzero second derivative (curvature) of the E x B flow on turbulence and transport. Much of the theory of E x B shear focuses on the effect of the shear in regions where the E x B flow has only a first spatial derivative.

Edge turbulence velocity preceding the L-H transition in NSTX

Cite as: Phys. Plasmas **28**, 032304 (2021); doi: 10.1063/5.0039153
Submitted: 1 December 2020 · Accepted: 23 February 2021 ·
Published Online: 19 March 2021

View Online Export Citation CrossMark

S. J. Zweben,[1,a] A. Diallo,[1] M. Lampert,[1] T. Stoltzfus-Dueck,[1] and S. Banerjee[2]

The low-to-high mode or L-H transition in tokamaks involves a sudden reduction in the edge turbulence level and a decrease in the edge plasma transport. The mechanism for the L-H transition is widely believed to be associated with changes in the poloidally averaged poloidal turbulence velocity………. In general, there were no clear and consistent changes in the poloidal velocity of the turbulence preceding the L-H transition in this database.

Gyrokinetic Current

[Lee and Qin, PoP **10**, 3196 (2003), Lee and White PoP **26**, 040701 (2019)]

$$\boxed{\begin{aligned}\mathbf{J}_{gc}(\mathbf{x}) &= \mathbf{J}_{\parallel gc}(\mathbf{x}) + \mathbf{J}^{M}_{\perp gc}(\mathbf{x}) + \mathbf{J}^{d}_{\perp gc}(\mathbf{x}) + \mathbf{J}^{E\times B}_{\perp gc}(\mathbf{x}) \\ &= \sum_\alpha q_\alpha \langle \int F_{\alpha gc}(\mathbf{R})(\mathbf{v}_\parallel + \mathbf{v}_\perp + \mathbf{v}_d + \mathbf{v}_{E\times B})\delta(\mathbf{R}-\mathbf{x}+\rho)d\mathbf{R}dv_\parallel d\mu\rangle_\varphi\end{aligned}}$$

$$\mathbf{v}_d = \frac{v_\parallel^2}{\Omega_\alpha}\hat{\mathbf{b}}\times(\hat{\mathbf{b}}\cdot\frac{\partial}{\partial\mathbf{R}})\hat{\mathbf{b}} + \frac{v_\perp^2}{2\Omega_\alpha}\hat{\mathbf{b}}\times\frac{\partial}{\partial\mathbf{R}}lnB \qquad \mathbf{v}_{E\times B} = \frac{c}{B}\mathbf{E}\times\hat{\mathbf{b}} \qquad \mu = v_\perp^2/2$$

$$\mathbf{J}^{M}_{\perp gc}(\mathbf{x}) = -\sum_\alpha \nabla_\perp \times \frac{c\hat{\mathbf{b}}}{B}p_{\alpha\perp} \qquad p_{\alpha\perp} = m_\alpha\int (v_\perp^2/2)F_{\alpha gc}(\mathbf{x})dv_\parallel d\mu$$

$$\mathbf{J}^{d}_{\perp gc} = \frac{c}{B}\sum_\alpha\left[p_{\alpha\parallel}(\nabla\times\hat{\mathbf{b}})_\perp + p_{\alpha\perp}\hat{\mathbf{b}}\times(\nabla lnB)\right] \qquad p_{\alpha\parallel} = m_\alpha\int v_\parallel^2 F_{\alpha gc}(\mathbf{x})dv_\parallel d\mu$$

$$\mathbf{J}^{M+d}_{\perp gc} = \mathbf{J}^{M}_{\perp gc} + \mathbf{J}^{d}_{\perp gc} \quad = \frac{c}{B}\sum_\alpha\left[\hat{\mathbf{b}}\times\nabla p_{\alpha\perp} + (p_{\alpha\parallel} - p_{\alpha\perp})(\nabla\times\hat{\mathbf{b}})_\perp\right]$$

$$\boxed{\mathbf{J}^{M+d}_{\perp gc} = \frac{c}{B}\sum_\alpha \hat{\mathbf{b}}\times\nabla_\perp p_{\alpha\perp}}$$

$$\longrightarrow \quad \boxed{\mathbf{J}_{\perp gc} = \frac{c}{B}\sum_\alpha \hat{\mathbf{b}}\times(\nabla_\perp p_{\alpha\perp} - n_\alpha q_\alpha \nabla_\perp\phi)}$$

This is a standalone equation and it is NOT a steady-state MHD equation

Lee and White, Phys. Plasmas 24, 081204 (2017); 25, 054702 (2018)

- Quasineutrality: $n_i \approx n_e$

- From Gyrokinetic Point of View: $n_i^{gc} + n_i^{pol} + n_i^{inho} = n_e^{gc}$

- At the pedestal: $n_i^{pol} + n_i^{inho} = 0$ for $n_i^{gc} = n_e^{gc}$

extra charge due to FLR effects

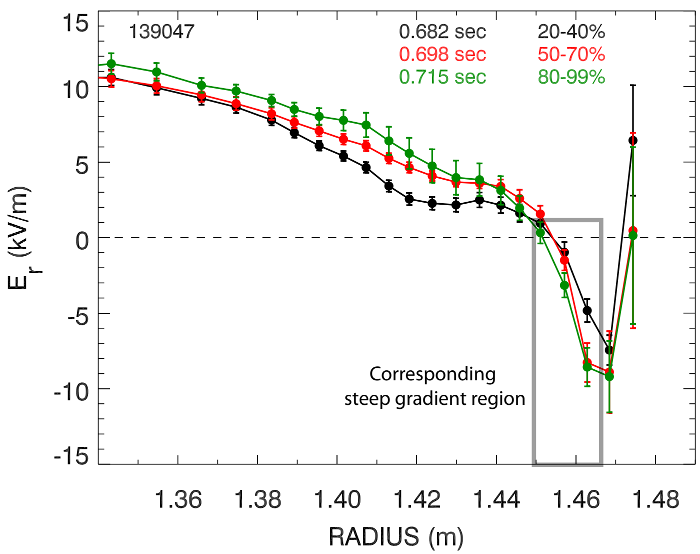
$$n = n^{gc} + \delta n = n^{gc} + \frac{1}{2T_i}\rho_i^2 \nabla_\perp^2 n^{gc} T_i = n^{gc} + \frac{\rho_i^2}{2T_i}\left(\frac{\partial^2 n^{gc} T_i}{\partial^2 r} + \frac{1}{r}\frac{\partial n^{gc} T_i}{\partial r}\right)$$

- GK Poisson's Equation: $\rho_s^2 \nabla_\perp \cdot n \nabla_\perp \frac{e\phi}{T_e} = -\delta n$

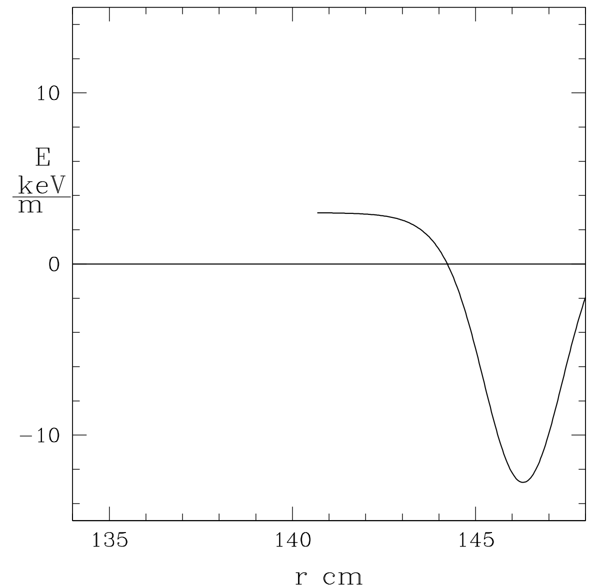
- GK Fields: $\boxed{eE_\perp = (1/2n)\nabla_\perp p_i + c}$ $p_i \equiv n^{gc} T_i$

NSTX Discharge and Theoretical Comparison

Radial electric field at the H-mode pedestal is believed to be caused by the charge separation resulting from the gyroradius differences between the electrons and the ions in the presence of sharp pressure gradients



A. Diallo *et al.*, Nucl. Fusion, **53**, 1 (2013)



Lee and White, Phys. Plasmas **24**, 081204 (2017)

Force balance equation based on gyrokinetics ions

$$n_i e\mathbf{E} = \nabla p_i - n_i e\frac{\mathbf{V}_i \times \mathbf{B}}{c}$$

It's not an MHD equilibrium solution

- Radial Direction: $n_i e E_r \approx \frac{\partial p_i}{\partial r} - \frac{n_i e}{c}(V_{\theta i} B_T)$

- Poloidal Drifts:

$$V_{\theta i} = V_{di} + V_{\perp i}$$

- Pressure balance

$$\frac{\partial p_i}{\partial r} = \frac{n_i e}{c}(V_{di} B_T)$$

- Radial Electric Field

$$E_r \approx -\frac{1}{c}(V_{\perp i} B_T)$$

Question: what are the different drifts active at the pedestal?

$$\boxed{V_{\perp i} = V_{\perp i}^{E\times B} + V_{\perp i}^{\nabla B} + V_{\perp i}^{\nabla\times B}}$$

[i.e., Lee and Qin, PoP '03]

$$V_{\perp i}^{\nabla B} = \frac{T_i c}{eB_T}\mathbf{b}\times\nabla ln B_T \qquad V_{\perp i}^{\nabla\times B} = \frac{T_i c}{eB_T}(\nabla\times\mathbf{b})_\perp$$

$$V_{\perp i}^{E\times B} = -cE_r/B_T$$

$$\boxed{E_r = \frac{1}{2n_i e}\frac{\partial p_i}{\partial r}}$$

[Lee and White, PoP '17 & '18]

$$V_{\perp i}^{E\times B} = -\frac{1}{2}\frac{c}{eB_T}\underline{\frac{1}{n_i}\frac{\partial p_i}{\partial r}} \propto \underline{\frac{\partial T_i}{\partial r} + \frac{T_i}{n_i}\frac{\partial n_i}{\partial r}}$$

•Answer: since T_i is small and magnetic gradients are small, it is most likely the dominant mechanism at the pedestal is

$$\boxed{V_{\perp i}^{E\times B}}$$

Gyrokinetic Quasineutrality at sharp density/pressure gradient

[Lee, PoP 26,556 (1983); Lee and Kolesnikov, PoP 16, 044506 (2009); Lee, PoP 23, 070705 (2016)]

FLR effects

$$\bar{n}(\mathbf{x}) = \int \left(1 + \underline{\frac{1}{4}\frac{v_\perp^2}{\Omega^2}\nabla_\perp^2}\right) F_{gc}(\mathbf{R}) dv_\parallel d\mu \longrightarrow \frac{n_i|_{particle}}{n_i|_{gc}} = 1 + \underline{\frac{1}{2}\rho_i^2 \frac{1}{p_i}\nabla_\perp^2 p_i}$$

FLR effects

— related to gyroviscosity in 2 fluid mom eqts [Scott, 2007]

From gyrokinetic Poisson's Eqtn $\longrightarrow$ $\boxed{\mathbf{v}_{E\times B} \approx -\frac{1}{2}\hat{\mathbf{b}} \times \frac{\nabla_\perp p_i}{p_i}\frac{cT_i}{eB}}$ -- Zonal Flow

$$\mathbf{J}_\perp^{E\times B}(\mathbf{x}) = \sum_\alpha q_\alpha \langle \int \mathbf{v}_{E\times B}(\mathbf{R}) F_\alpha(\mathbf{R}) \delta(\mathbf{R} - \mathbf{x} + \rho) d\mathbf{R} d\mu dv_\parallel \rangle_\varphi$$

$$\mathbf{J}_\perp = \frac{c}{B}\hat{\mathbf{b}} \times \nabla p + e n_i \frac{\rho_i^2}{2}\left[\nabla_\perp^2 \mathbf{v}_{E\times B} + \frac{\mathbf{v}_{E\times B}}{p_i}\nabla_\perp^2 p_i\right]$$

Difference in gyroradius effects between ions and electrons

$$\boxed{\mathbf{J}_\perp \approx \frac{c}{B}\hat{\mathbf{b}} \times (\nabla p)\left[1 - \frac{1}{2}\rho_i^2 \frac{\nabla_\perp^2 p}{p}\right]}$$

-- FLR modification of pressure balance

gyroviscosity

Lee and White, "FLR effects at the H-mode pedestal and the related force-free steady state," Phys. Plasmas 26, 040701 (2019)

- FLR Modified Pressure balance:

$$\mathbf{J}_\perp \approx \frac{c}{B}\hat{\mathbf{b}} \times (\nabla p_i)\left[1 - \frac{1}{2}\rho_i^2 \frac{\nabla_\perp^2 p_i}{p_i}\right] \quad \text{— related to gyroviscosity}$$

- H-mode like pressure profile: $\left[\begin{array}{ll} \nabla_\perp p_i \approx 0 & \text{at the core} \\ p_i \propto exp(-\sqrt{2}r/\rho_i) & \text{at the edge} \end{array}\right.$

$$\boxed{\mathbf{J}_\perp \to 0}$$

- Force-free Steady State: $\boxed{\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}_\parallel}$ — spontaneous relaxation

- Woltjer/Taylor Equilibrium State: $\nabla \times \mathbf{B} = \mu \mathbf{B}$

Need simulation and experimental data on poloidal current near the pedestal region to compare with the theory

Energy exchange dynamics across L–H transitions in NSTX

A. Diallo[1], S. Banerjee[2], S.J. Zweben[1] and T. Stoltzfus-Dueck[1]

Nucl. Fusion **57** (2017) 066050 A. Diallo *et al*

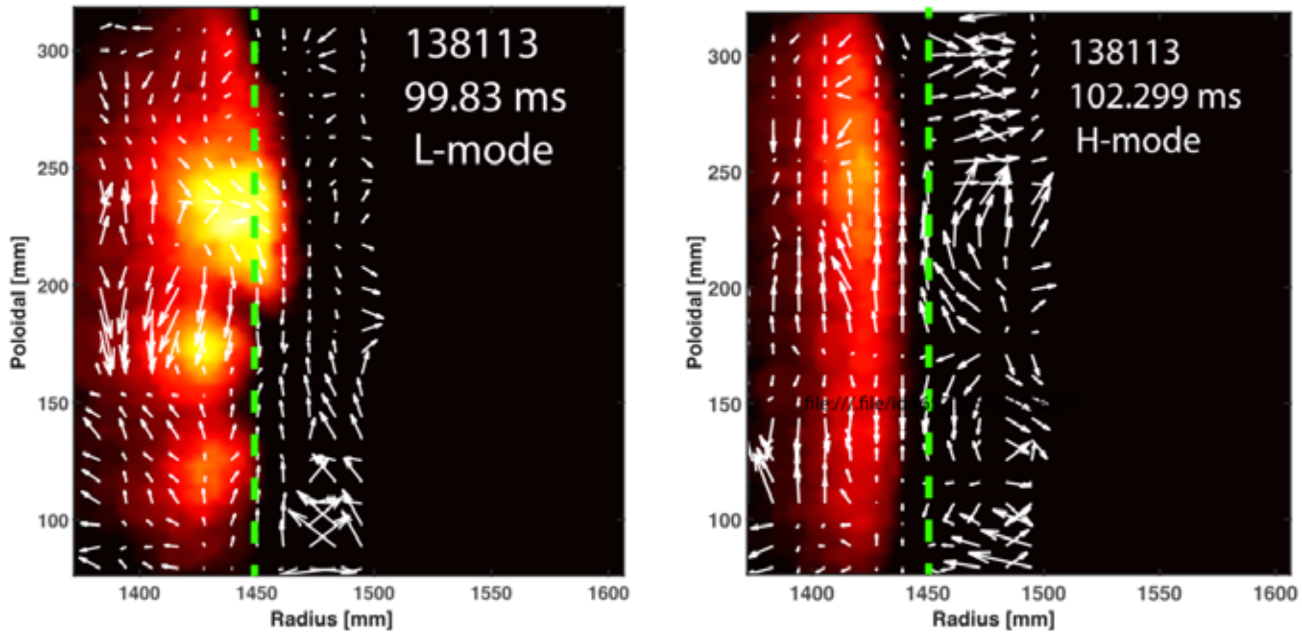
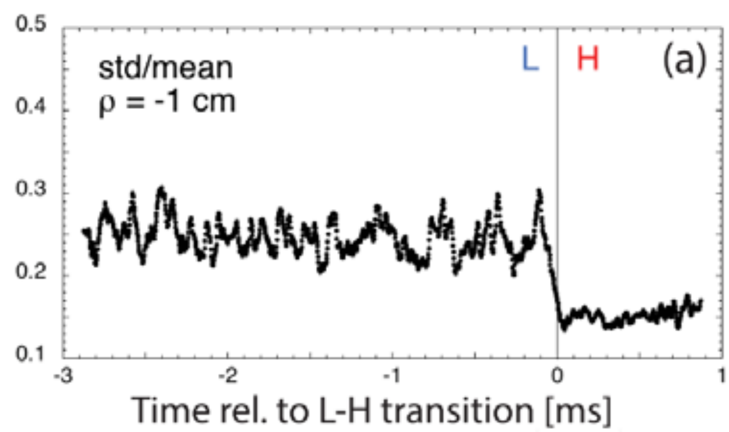


Figure 5. Examples of the GPI intensity images where the arrows represent the velocity vectors. The vertical green dotted line indicates the separatrix location (with ±1 cm uncertainty).



Gyrokinetic Vlasov Equation in General Geometry

[For example, W. W. Lee, PoP 2016]

$$\frac{\partial F_\alpha}{\partial t} + \frac{d\mathbf{R}}{dt} \cdot \frac{\partial F_\alpha}{\partial \mathbf{R}} + \frac{dv_\parallel}{dt} \frac{\partial F_\alpha}{\partial v_\parallel} = 0$$

$$\frac{d\mathbf{R}}{dt} = v_\parallel \mathbf{b}^* + \frac{v_\perp^2}{2\Omega_{\alpha 0}} \hat{\mathbf{b}}_0 \times \nabla ln B_0 - \frac{c}{B_0} \nabla \bar{\Phi} \times \hat{\mathbf{b}}_0$$

$$\frac{dv_\parallel}{dt} = -\frac{v_\perp^2}{2} \mathbf{b}^* \cdot \nabla ln B_0 - \frac{q_\alpha}{m_\alpha} \left(\mathbf{b}^* \cdot \nabla \bar{\Phi} + \underline{\frac{1}{c} \frac{\partial \bar{A}_\parallel}{\partial t}} \right)$$

Startsev and Lee PoP **21**, 022505 (2014)
Bao, Lin and Lu, PoP **25**, 022515 (2018)

$$\Omega_{\alpha 0} \equiv q_\alpha B_0 / m_\alpha c$$

$$\bar{\Phi} \equiv \bar{\phi} - \overline{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}/c \qquad \underline{\overline{\mathbf{v}_\perp \cdot \mathbf{A}_\perp} = -\frac{1}{2\pi} \frac{eB_0}{mc} \int_0^{2\pi} \int_0^{\rho} \delta B_\parallel r dr d\theta}$$

Gyrophase Average

Porazik and Lin, Comm. Comp. Phys. **10**, 899 (2011)

$$\mathbf{b}^* \equiv \mathbf{b} + \frac{v_\parallel}{\Omega_{\alpha 0}} \hat{\mathbf{b}}_0 \times (\hat{\mathbf{b}}_0 \cdot \nabla) \hat{\mathbf{b}}_0 \qquad \mathbf{b} = \hat{\mathbf{b}}_0 + \frac{\nabla \times \bar{\mathbf{A}}}{B_0}$$

$$F_\alpha = \sum_{j=1}^{N_\alpha} \delta(\mathbf{R} - \mathbf{R}_{\alpha j}) \delta(\mu - \mu_{\alpha j}) \delta(v_\parallel - v_{\parallel \alpha j})$$

- Associated Gyrokinetic Field Equations:

$$\nabla^2\phi + \frac{\omega_{pi}^2}{\Omega_i^2}\nabla_\perp^2\phi = -4\pi\sum_\alpha q_\alpha \int \overline{F}_\alpha dv_\parallel d\mu \qquad \text{-- for} \qquad k_\perp^2\rho_i^2 \ll 1$$

$$\nabla^2\mathbf{A} - \underline{\frac{1}{v_A^2}\frac{\partial^2\mathbf{A}_\perp}{\partial t^2}} = -\frac{4\pi}{c}\sum_\alpha q_\alpha \int \mathbf{v}\bar{F}_\alpha dv_\parallel d\mu$$

Negligible for $\omega^2 \ll k_\perp^2 v_A^2$

$$\mathbf{v}_p^L = -(mc^2/eB^2)(\partial\nabla_\perp\phi/\partial t)$$

$$\mathbf{v}_p^T = -(mc/eB^2)(\partial^2\mathbf{A}_\perp/\partial^2 t)$$

$$\mu_B \equiv \mu/B \approx const. \qquad \mu = v_\perp^2/2$$

- Energy Conservation: $\Phi \equiv \phi - \overline{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}/c$

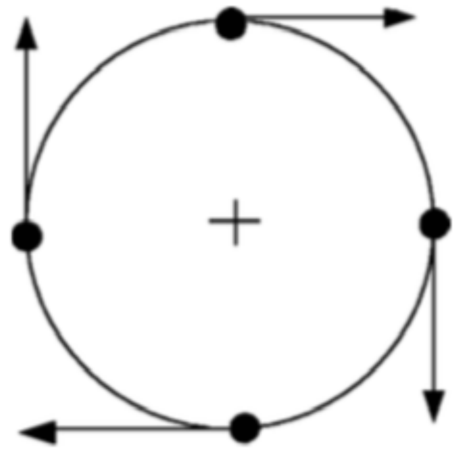
$$\frac{d}{dt}\left\langle \int (\frac{1}{2}v_\parallel^2 + \mu)(m_e F_e + m_i F_i) dv_\parallel d\mu + \frac{\omega_{ci}^2}{\Omega_i^2}\frac{|\nabla_\perp\Phi|^2}{8\pi} + \frac{|\nabla A_\parallel|^2}{8\pi}\right\rangle_{\mathbf{x}} = 0$$

Calculation of Ion Density and Perpendicular Current in GK PIC Codes with Inhomogeneous Loading

$$\rho(\mathbf{x}) = \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$= \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \int \delta(\mathbf{R} - \mathbf{R}_{\alpha j}) \delta(\mathbf{x} - \mathbf{R} - \rho_{\alpha j}) d\mathbf{R} \rangle_\varphi$$

$$= \sum_\alpha q_\alpha \sum_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}} \sum_{j=1}^{N} e^{-i\mathbf{k}\cdot\mathbf{R}_{\alpha j}} \langle e^{-i\mathbf{k}\cdot\rho_{\alpha j}} \rangle_\varphi / V$$



4-point average
for ion density and current

[Lee JCP ’87, Lee and Qin POP ’03]

$$\mathbf{J}^M_{\perp gc}(\mathbf{x}) = \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \mathbf{v}_{\perp\alpha j} \delta(\mathbf{x} - \mathbf{x}_{\alpha j}) \rangle_\varphi$$

$$= \sum_\alpha q_\alpha \sum_{j=1}^{N} \langle \int \mathbf{v}_{\perp\alpha j} \delta(\mathbf{R} - \mathbf{R}_{\alpha j}) \delta(\mathbf{x} - \mathbf{R} - \rho_{\alpha j}) d\mathbf{R} \rangle_\varphi$$

$$= \sum_\alpha q_\alpha \sum_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}} \sum_{j=1}^{N} e^{-i\mathbf{k}\cdot\mathbf{R}_{\alpha j}} \langle \mathbf{v}_{\perp\alpha j} e^{-i\mathbf{k}\cdot\rho_{\alpha j}} \rangle_\varphi / V$$

Gyrokinetic MHD Equations

[Lee, PoP **23**, 070705 (2016); Lee, Hudson and Ma, PoP **24**, 124508 (2017)]

Vorticity Equation: $\frac{d}{dt}\nabla_\perp^2\phi - 4\pi\frac{v_A^2}{c^2}\nabla\cdot(\mathbf{J}_\parallel + \mathbf{J}_\perp) = 0$ — similar but more complete than Strauss Equations

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} - \frac{c}{B}\nabla\phi\times\mathbf{b}\cdot\nabla$$

Ohm's Law: $E_\parallel \equiv -\frac{1}{c}\frac{\partial A_\parallel}{\partial t} - \mathbf{b}\cdot\nabla\phi \approx -\frac{1}{en_e}\frac{\partial p_{\parallel e}}{\partial x_\parallel} + \eta J_\parallel,$

Equations of State: $\frac{dp_{\parallel e}}{dt} = 2E_\parallel J_\parallel \qquad \frac{dp_\perp}{dt} = 0 \qquad p = nT$

Energy Conservation: $\frac{\partial}{\partial t}\int\frac{1}{8\pi}\left(|\nabla_\perp\phi|^2 + \frac{v_A^2}{c^2}|\nabla A_\parallel|^2\right)d\mathbf{x} = -\frac{v_A^2}{c^2}\int\mathbf{E}_\perp\cdot\mathbf{J}_\perp d\mathbf{x},$

Ampere's Law: $\nabla^2 A_\parallel = -\frac{4\pi}{c}J_\parallel$

MHD equilibrium: $\nabla\cdot(\mathbf{J}_\parallel + \mathbf{J}_\perp) = 0$

Conclusion

— We believe the ExB flow is the result of the pedestal formation which reduces the transport, not the cause for the reduction. The pedestal formation gives rise to the Er well due to charge separation.

— We argue that this spontaneous phase transition for a magnetic confined plasma from one state to another can be explained thermodynamically as the evolution of the system to the minimum magnetic energy state.

— To verify this transition, we need a fully electromagnetic gyrokinetic code and/or a gyrokinetic-MHD code by taking into account the charge separation at the plasma edge caused by the steep pressure gradients due to the finite Larmor radius (FLR) effects. Namely, study the transition physics as an initial value problem

— What about the experimental measurements? What about the use of hydrogen isotopes?